

Perpendicular Diffusion in the Transport of Solar Energetic Particles from Unconnected Sources: The Counter-streaming Particle Beams Revisited

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Received _____; accepted _____

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ABSTRACT

In some solar energetic particle (SEP) events, a counter-streaming particle beam with a deep depression of flux at $\sim 90^\circ$ pitch angle during the beginning phase is observed. Two different interpretations exist in the community to explain this interesting phenomenon. One explanation invokes the hypothesis of an outer reflecting boundary or a magnetic mirror beyond the observer. The other one considers the effect of the perpendicular diffusion on the transport process of SEPs in the interplanetary space. In this work, we revisit the problem of the counter-streaming particle beams observed in SEP events and discuss the possible mechanisms responsible for the formation of this phenomenon. We clarify some results in previous works.

Subject headings: interplanetary medium – magnetic fields – solar–terrestrial relations
– Sun: flares – Sun: particle emission

1. Introduction

Solar energetic particles (SEPs) are charged particles of up to GeV energies occasionally emitted by the Sun. Generally speaking, SEPs are associated with solar flares or/and coronal mass ejections (CMEs), although the relative roles of flares and CME-driven shocks in producing high-energy particles are not completely understood. Theoretically, SEPs observed in the interplanetary space provide fundamental information regarding the acceleration and transport process of charged particles. Therefore, the subject has become a focus of space physics, astrophysics, and plasma physics. Furthermore, achieving a better understanding of the transport and acceleration of charged particles is essential for space weather research regarding SEP events.

The diffusion mechanism of SEPs transporting in interplanetary space consists of two components, namely, parallel diffusion along and perpendicular diffusion across the mean magnetic field. The parallel diffusion plays an obviously important role in the propagation of SEPs, so it has been extensively investigated. The perpendicular diffusion, however, was ignored for quite a long time in previous studies of SEP transport in interplanetary space. Recently, the importance of perpendicular diffusion has been gradually and increasingly realized by the numerical modeling community (e.g., Zhang et al. 2009; He et al. 2011; Giacalone & Jokipii 2012; Dröge et al. 2014; He & Wan 2015; Strauss & Fichtner 2015) and the observational community (e.g., Zhang et al. 2003; He & Wan 2013; Dresing et al. 2012, 2014) of SEP transport and distribution. The effective perpendicular diffusion and its important effects on the transport process of SEPs were seen in these numerical or observational studies.

There are some interesting phenomena in the research field of SEP events, such as SEP reservoirs, east-west longitudinally asymmetric distribution, and counter-streaming particle beams. The SEP reservoir refers to the phenomenon where the particle intensities

evolve similarly in time with nearly the same decay rate during the late phase of the SEP events. The SEP reservoirs are observed by spacecraft at both low and high heliolatitudes, and by spacecraft at very different heliolongitudes and radial distances. In addition, the energetic particle reservoirs are observed during both isolated SEP events and a sequence of SEP events. The SEP reservoirs are detected not only in proton data, but also in electron and heavy-ion data. There exist some different viewpoints in the community to explain the formation of the SEP reservoirs in the heliosphere. One explanation is that the perpendicular diffusion mechanism effectively and uniformly distributes the charged particles in longitude and latitude to form the observed SEP reservoirs (e.g., McKibben 1972; McKibben et al. 2003; Zhang et al. 2009; He et al. 2011; He & Wan 2015). Another explanation is that there exist outer reflecting boundaries or diffusion barriers in the interplanetary space, formed by the plasma disturbances originating from intense solar bursts, to delay the SEPs from escaping to larger radial distances and uniformly redistribute them in longitude and latitude (e.g., Roelof et al. 1992; Reames et al. 1997; Tan et al. 2009). However, as He & Wan (2015) pointed out, it is difficult to imagine such an “overwhelming” reflecting boundary or diffusion barrier covering all of the longitudes, all of the latitudes, and even all of the radial distances. For the formation of SEP reservoirs, there is also a third explanation combining the two aforementioned mechanisms (e.g., Lario et al. 2003).

The east-west longitudinally asymmetric distribution of SEPs refers to the phenomenon that with the same longitude separation between the solar source and the magnetic footpoint of the observer, the flux of the SEP event originating from the solar source located at eastern side of the nominal magnetic footpoint of the observer is larger than that of the SEP event originating from the source located at the western side. This phenomenon was found in the numerical simulations of the multidimensional transport equation of SEPs (He et al. 2011; He & Wan 2015) and was also proven by the spacecraft observations (He & Wan 2013; Dresing et al. 2014). We conclude that the longitudinally asymmetric

distribution of SEPs results from the east-west azimuthal asymmetry in the geometry of the Parker interplanetary magnetic field as well as the effects of perpendicular diffusion on the transport processes of SEPs in the heliosphere (He et al. 2011; He & Wan 2013, 2015). Other interpretations for this phenomenon also exist (e.g., Lario et al. 2014).

The counter-streaming particle beam is the phenomenon where during the onset phase of an SEP event, a significant number of particles could move toward the Sun, while the SEP intensities at $\sim 90^\circ$ pitch angle still stay deeply depressed. Two different mechanisms have been provided to explain this SEP phenomenon. On the one hand, some authors suggested that the counter-streaming particle beams observed in the SEP events result from an outer reflecting boundary or a nearby magnetic mirror outside of 1 AU (e.g., Tan et al. 2009, 2011). They further suggested that a counter-streaming particle beam with a deep depression around 90° pitch angle during the beginning of the SEP event is an evidence for the presence of an outer reflecting boundary. On the other hand, a model calculation of SEP transport with the effect of perpendicular diffusion in the three-dimensional interplanetary magnetic field showed that the counter-streaming particle beams with a deep depression at $\sim 90^\circ$ pitch angle can be reproduced without invoking the hypothesis of an outer reflecting boundary or a magnetic mirror (Qin et al. 2011). Other transport simulations including the effects of pitch-angle diffusion and reflecting boundary were also presented to account for the back-streaming electrons (e.g., Kartavykh et al. 2013). However, Tan et al. (2012) argued against the existence of scattering and perpendicular diffusion experienced by the low energy electrons in the SEP events and stated that “the simulation result shown in Figure 3 of Qin et al. (2011) does not exhibit a particle depression at $\mu \sim 0$ as observed by Tan et al. (2009), contrary to their claim”. Therefore, it is necessary and important to revisit the problem of the counter-streaming particle beams and clarify some confusing results in the previous works.

In this paper, we revisit the phenomenon of the counter-streaming particle beams observed in the onset phase of SEP events to clarify some confusing results in the previous works. Specifically, in Section 2, we present the spacecraft observation of the counter-streaming particle beam in the 2001 September 24 SEP event. In Section 3, we present a model calculation of SEP propagation with perpendicular diffusion in the three-dimensional interplanetary magnetic field, and fit to the SEP observation in the 2001 September 24 event. In Section 4, we discuss the fitting results and the possible mechanisms responsible for the phenomenon of the counter-streaming particle beams. A summary of our results will be provided in Section 5.

2. Counter-streaming Particle Beam: 2001 September 24 SEP Event

The solar flare associated with the 2001 September 24 SEP event occurred at S16E23, starting at 09:32 UT, reaching optical emission maximum at 10:38 UT, and ending at 11:09 UT. This SEP event was observed by the Three-Dimensional Plasma (3DP) instrument onboard the Wind spacecraft. During the beginning phase of this SEP event, the so-called counter-streaming particle beam phenomenon was observed. The red solid lines in Figure 1 indicate the ~ 40 keV electron pitch-angle distributions observed by the Wind/3DP instrument during the 2001 September 24 SEP event. The angular distributions of particles are obtained from sectorized measurements of eight directions. The time resolution of the Wind/3DP data we use in this work is 5 s. The increasing time labeled in red from the bottom to top panels indicates when the pitch-angle distribution data were measured by Wind/3DP. The panels from bottom to top are plotted in time intervals of 15 minutes. Following previous works related to this SEP event, the X-axis coordinate in Figure 1 is set so that the pitch-angle cosine $\mu = -1$ corresponds to charged particles moving away from the Sun.

The Wind/3DP observations, denoted by the red solid lines in Figure 1, show that in the very beginning of the 2001 September 24 SEP event, the SEP flux only arises on the right side, i.e., at $\mu \lesssim -0.2$. It means that all particles are nearly propagating away from the Sun. After 30 minutes, however, electrons with $\mu \gtrsim 0.7$ start to appear and increase gradually. Interestingly, during this evolution process, the electrons with $\mu \sim 0$ were still absent or had very low intensity. Therefore, the so-called counter-streaming particle beam phenomenon was observed in this SEP event. Tan et al. (2009) proposed that there is no scattering of incident electrons because the flux near 90° pitch-angle (corresponding to $\mu \sim 0$) is nearly 0, and further suggested that the electron flux increases at $\mu \gtrsim 0.7$ are mainly formed by reflected electrons from a stronger magnetic field configuration beyond the location of the observer, i.e., the Wind spacecraft at 1 AU. Tan et al. (2009) claimed that the presence of a counter-streaming particle beam with an intensity depression of electrons at $\sim 90^\circ$ pitch angle ($\mu \sim 0$) could be a strong evidence for the existence of a nearby outer reflecting boundary of SEPs.

In the next section, we will present a numerical model of SEP propagation with perpendicular diffusion in the three-dimensional interplanetary magnetic field. The simulation results will be used to explain the observed counter-streaming particle beam in the 2001 September 24 SEP event.

3. Numerical Simulations of the 2001 September 24 SEP Event

3.1. Numerical Model

The multidimensional Fokker-Planck focused transport equation that governs the gyrophase-averaged distribution function $f(\mathbf{x}, \mu, p, t)$ of charged particles can be written as (e.g., Schlickeiser 2002; Zhang et al. 2009; He et al. 2011; He & Wan 2015; Dröge et al.

2010, 2014)

$$\begin{aligned} & \frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \mathbf{V}^{sw} \cdot \nabla f + \frac{dp}{dt} \frac{\partial f}{\partial p} + \frac{d\mu}{dt} \frac{\partial f}{\partial \mu} \\ & - \frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right) - \frac{\partial}{\partial x} \left(\kappa_{xx} \frac{\partial f}{\partial x} \right) - \frac{\partial}{\partial y} \left(\kappa_{yy} \frac{\partial f}{\partial y} \right) = Q(\mathbf{x}, p, t), \end{aligned} \quad (1)$$

where \mathbf{x} is the particle's position, z is the coordinate along the magnetic field spiral, p is the particle's momentum, μ is the pitch-angle cosine of the particle, t is time, v is the particle speed, \mathbf{V}^{sw} is the solar wind speed, κ_{xx} and κ_{yy} are the perpendicular diffusion coefficients, and Q is the source term. The term dp/dt represents the adiabatic cooling effect and can be written as (e.g., Skilling 1971)

$$\frac{dp}{dt} = -p \left[\frac{1 - \mu^2}{2} \left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} \right) + \mu^2 \frac{\partial V_z^{sw}}{\partial z} \right]. \quad (2)$$

The term $d\mu/dt$, including the effects of magnetic focusing and the divergence of solar wind flows, can be written as (e.g., Roelof 1969; Isenberg 1997; Kóta & Jokipii 1997)

$$\begin{aligned} \frac{d\mu}{dt} &= \frac{1 - \mu^2}{2} \left[-\frac{v}{B} \frac{\partial B}{\partial z} + \mu \left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2 \frac{\partial V_z^{sw}}{\partial z} \right) \right] \\ &= \frac{1 - \mu^2}{2} \left[\frac{v}{L} + \mu \left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2 \frac{\partial V_z^{sw}}{\partial z} \right) \right], \end{aligned} \quad (3)$$

where B is the average interplanetary magnetic field, and the magnetic focusing length L is defined by $L = (\mathbf{z} \cdot \nabla \ln B)^{-1}$.

We use the form of the pitch-angle diffusion coefficient as (e.g., Beeck & Wibberenz 1986; He et al. 2011; He & Wan 2015)

$$D_{\mu\mu}^r = D_{\mu\mu} / \cos^2 \psi = D_0 v R^{-1/3} (|\mu|^{q-1} + h) (1 - \mu^2), \quad (4)$$

where D_0 is a constant indicating the magnetic turbulence strength and R is the particle rigidity. The constant h is needed to model the particles' scattering ability through $\mu = 0$ (90° pitch angle). In order to simulate the nonlinear effect to cause large $D_{\mu\mu}$ at $\mu = 0$, we

use a relatively large value of $h = 0.2$. The constant q is related to the power spectrum of magnetic turbulence in the inertial range, chosen to be $5/3$ in our numerical model.

We employ the time-backward Markov stochastic process method to numerically solve the five-dimensional Fokker-Planck transport equation (1). After the operation with the Markov stochastic process method, we can obtain five time-backward stochastic differential equations, which are recast from the Fokker-Planck transport equation (1), as follows (e.g., Zhang et al. 2009; He et al. 2011; He & Wan 2015):

$$\begin{aligned}
dX &= \sqrt{2\kappa_{xx}}dW_x(s) - V_x^{sw}ds \\
dY &= \sqrt{2\kappa_{yy}}dW_y(s) - V_y^{sw}ds \\
dZ &= -(\mu V + V_z^{sw})ds \\
d\mu &= \sqrt{2D_{\mu\mu}}dW_\mu(s) \\
&\quad - \frac{1-\mu^2}{2} \left[\frac{V}{L} + \mu \left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} - 2\frac{\partial V_z^{sw}}{\partial z} \right) \right] ds \\
&\quad + \left(\frac{\partial D_{\mu\mu}}{\partial \mu} + \frac{2D_{\mu\mu}}{M+\mu} \right) ds \\
dP &= P \left[\frac{1-\mu^2}{2} \left(\frac{\partial V_x^{sw}}{\partial x} + \frac{\partial V_y^{sw}}{\partial y} \right) + \mu^2 \frac{\partial V_z^{sw}}{\partial z} \right] ds,
\end{aligned} \tag{5}$$

where (X, Y, Z) is the pseudo-position, V is the pseudo-speed, P is the pseudo-momentum, and $W_x(t)$, $W_y(t)$, and $W_\mu(t)$ are Wiener processes.

In Equation (1), the source term Q is assumed to be the following form (e.g., Reid 1964; He et al. 2011)

$$Q(r \leq 0.01AU, E_k, \theta, \phi, t) = \frac{C}{t} \frac{E_k^{-\gamma}}{p^2} \exp \left(-\frac{\tau_c}{t} - \frac{t}{\tau_L} \right) \xi(\theta, \phi), \tag{6}$$

where γ is the power-law spectrum index of source particles, set to be 3, τ_c and τ_L are the time constants indicating the rise and decay timescales of the particle release profile in the solar corona, which are set to be $\tau_c = 3.30$ hr and $\tau_L = 6.74$ hr in this work, respectively, and $\xi(\theta, \phi)$ is a function describing the latitudinal and longitudinal distribution of SEP

injection strength in solar sources. In this work, an SEP source with limited coverage in latitude and longitude is used. In the numerical simulations, we need to use an outer absorptive boundary of pseudoparticles, which is set at $r = 50$ AU in this work. According to the Wind spacecraft measurements during the 2001 September 24 SEP event, in the simulations we use a solar wind speed $V^{sw} = 450 \text{ km s}^{-1}$.

The numerical modeling results were usually normalized to compare with the observation data of the SEP events, which will be done in the following. In each figure of simulation results that follows, the normalization factor is the same for plotting all the panels of that figure. We also note that in each figure, the normalization factor for plotting the simulation results with perpendicular diffusion is different from that for plotting the simulation results without perpendicular diffusion, since the particle intensity of the latter case is much larger than that of the former case, due to a uniform SEP source used in the latter case.

3.2. Simulation Results

In this case study, we set the radial mean free path to be constant with the value $\lambda_r = 0.15$ AU (corresponding to the parallel mean free path $\lambda_{\parallel} = 0.34$ AU at 1 AU). In the simulations with perpendicular diffusion, the perpendicular mean free paths are set to the constant value $\lambda_x = \lambda_y = 0.03$ AU for 40 keV electrons. The blue solid lines in Figure 1 present the simulation results of the 2001 September 24 SEP event. The increasing time labeled in blue in the bottom to top panels indicates when the particle pitch-angle distributions occur in the numerical simulations. As we can see, the simulation time in each panel is set the exact same as the observation time. The evolution behavior of the particles' pitch-angle distribution in the simulation scenario with perpendicular diffusion is similar to the Wind/3DP observation of the 2001 September 24 SEP event. In the beginning, the

observer at 1 AU only detected the energetic electrons moving away from the Sun, i.e., streaming in the anti-sunward direction. Later at around 11:52:30 UT, the electrons with pitch-angle cosine $\mu \gtrsim 0.5$ began to appear. After that, the electron intensities in both the anti-sunward and sunward directions gradually increased with time, while during this period the electron flux at $\mu \sim 0$ was still depressed. In the top two panels, the simulated electron flux at $\mu \sim 0$ gradually increased. At late stage of the 2001 September 24 SEP event, the Wind/3DP observation also showed that the electron intensity at $\mu \sim 0$ began to appear. The blue dashed lines in Figure 1 indicate the simulation results without perpendicular diffusion, but with a uniform SEP source. One can see that in this scenario, the electron intensity in each panel monotonically decreases with increasing pitch-angle cosine μ , without any intensity depression at $\mu \sim 0$. Therefore, the direct comparison between the simulation results obtained with and without perpendicular diffusion suggests that the perpendicular diffusion can cause the so-called counter-streaming particle beams with a deep intensity depression at $\mu \sim 0$.

As we know, in the interplanetary space, the physical circumstances and conditions for SEP diffusion and propagation are very complicated and dynamic. In our simulations of SEP propagation, we used some necessary assumptions for simplification in the numerical modeling. Therefore, it is difficult to exactly simulate the entire temporal evolution of SEP events at a given position in the interplanetary space. In Figure 1, in order to match the timing of the 2001 September 24 SEP event, we set the simulation time in each panel the exact same as the observation time. Therefore, the fitting of the particle pitch-angle distribution is not very perfect. However, the basic evolution features of the 40 keV electrons in the 2001 September 24 SEP event have been successfully reproduced in our numerical simulations based on the five-dimensional Fokker-Planck transport equation.

To better fit the particles' pitch-angle distribution, we replot the simulation results

with perpendicular diffusion in Figure 2 without exactly matching the timing of the SEP event. The blue solid curves in Figure 2 show the numerical simulation results with perpendicular diffusion, plotted in a rough-timing manner. We note that the normalization factors for plotting the simulation results in Figure 2 are different from those in Figure 1. As one can see, the simulation results with perpendicular diffusion show excellent agreement with the evolution of the electron pitch-angle distributions (shown with red solid lines in Figure 1) observed by the Wind/3DP instrument during the beginning of the 2001 September 24 SEP event. In this rough-timing fashion, a much better fitting of the simulation with perpendicular diffusion to the observation data is obvious to see. In the very beginning of the SEP event, only the energetic electrons moving away from the Sun were observed at 1 AU. Later, the energetic electrons at $\mu \gtrsim 0.5$ began to appear. With increasing time, the intensities of electrons both moving away from and toward the Sun gradually increased. However, the electrons with $\mu \sim 0$ were still absent during this period. Therefore, the counter-streaming particle beam with a deep depression at $\sim 90^\circ$ pitch angle was evidently reproduced in the numerical simulation with perpendicular diffusion. The blue dashed curves in Figure 2 present the simulation results without perpendicular diffusion. As shown in Figure 1, during the SEP event onset the simulation without perpendicular diffusion in Figure 2 does not display any observational features of the so-called counter-streaming particle beam with deep intensity depression at $\mu \sim 0$. The strong comparison between the simulation results with and without perpendicular diffusion suggests that the counter-streaming particle beams can be caused by the perpendicular diffusion of SEPs.

4. Discussion on the Possible Mechanisms Responsible for Counter-streaming Particle Beams

The work Tan et al. (2009) discussed the phenomenon of the counter-streaming particle beams observed in SEP events and proposed that an outer reflecting boundary or a nearby magnetic mirror outside of 1 AU causes this SEP phenomenon. Furthermore, they suggested that a counter-streaming particle beam with a deep intensity depression around the 90° pitch angle during the beginning stage of the SEP event is an evidence for the presence of an outer reflecting boundary. In some specific circumstances, an outer reflecting boundary or a magnetic mirror could be formed by large-scale plasma disturbances launched during periods of intense solar activity. The enhanced magnitude of the interplanetary magnetic field formed at these reflecting boundaries could influence the transport processes of charged particles, even change their transport directions in the interplanetary space, e.g., from the anti-sunward to sunward directions. If the number of particles streaming toward the Sun after being reflected from a reflecting boundary is quite considerable, and the particles crossing the magnetic field lines are very scarce, then the so-called counter-streaming particle beam with a deep depression of flux at $\sim 90^\circ$ pitch angle could form. However, it requires that the configuration of the disturbed interplanetary magnetic field is exquisite enough. In addition, so far no explicit or quantitative mechanism of the outer reflecting boundaries has been specified in the community. Therefore, to present a mathematically tractable description should be the critical task for the mechanism of reflecting boundary.

Generally, the propagation of SEPs in the interplanetary magnetic field mainly consists of the along-field and the cross-field processes, known as the parallel and the perpendicular components, respectively. In this work, we provide an alternative mechanism for the formation of counter-streaming particle beams. In our explanation, the perpendicular diffusion plays a significant role in the formation of counter-streaming particle beams. Our

explanation is based on the numerical modeling of the multidimensional Fokker-Planck transport equation. In our modeling, we use a Parker-type interplanetary magnetic field and a constant solar wind speed $V^{sw} = 450 \text{ km s}^{-1}$. Accordingly, we can easily deduce that during the 2001 September 24 SEP event, the nominal magnetic footpoint of the observer (i.e., the Wind spacecraft) was at $\sim 50.4^\circ$ W in heliographic longitude and $\sim 7.0^\circ$ N in heliographic latitude. Therefore, the separation between the nominal magnetic footpoint of the Wind spacecraft and the solar flare location (S16E23) was $\sim 73.4^\circ$ in longitude and $\sim 23.0^\circ$ in latitude. In addition to parallel diffusion along the mean magnetic field, the SEPs will experience perpendicular diffusion and cross the interplanetary magnetic field. Therefore, the SEPs originating from acceleration regions with limited coverage can be observed by distant spacecraft with large longitudinal or/and latitudinal separations. In our simulation with perpendicular diffusion, we use $\lambda_r = 0.15 \text{ AU}$ and $\lambda_x = \lambda_y = 0.03 \text{ AU}$. Near the Sun, the magnetic focusing effect plays an important role in the transport of SEPs; while at larger radial distances, the significance of the adiabatic focusing is largely reduced (e.g., Schlickeiser & Shalchi 2008; He & Wan 2012a; He & Schlickeiser 2015; Shalchi & Danos 2013; Tautz et al. 2014). Due to the relatively large parallel mean free path used in the modeling, quite a number of energetic electrons will transport approximately along the magnetic field lines and reach radial distances larger than 1 AU before being scattered back. Meanwhile, as a result of perpendicular diffusion, the energetic electrons will move in the perpendicular direction to cross the magnetic field lines, particularly at larger radial distances. These cross-field electrons can move onto the field line connecting the observer whose magnetic footpoint is tens of degrees in longitude and latitude away from the SEP source. Afterwards, some of these electrons will be scattered back there and move toward the Sun, i.e., in the sunward direction. The observer at $\sim 1 \text{ AU}$ can detect two different types of particles: some particles crossed the field lines at smaller radial distances $r \lesssim 1 \text{ AU}$; while other particles crossed the field lines at larger radial distances $r \gtrsim 1 \text{ AU}$. The

former particles are observed as moving in the anti-sunward direction; while the latter particles are detected as streaming in the sunward direction. Therefore, in the beginning of the SEP event, a counter-streaming particle beam with a deep depression of intensity at $\sim 90^\circ$ pitch-angle is formed. After that, particles with intense scattering begin to appear at the observer, so the intensity at $\mu \sim 0$ begins to increase. The physical scenario of the formation of counter-streaming particle beams via perpendicular diffusion is sketched in Figure 3.

We note that in this work, we use some simplifications in the modeling of SEP transport. For instance, we use a Parker interplanetary magnetic field and a constant solar wind speed $V^{sw} = 450 \text{ km s}^{-1}$. For the diffusion coefficients, we use a constant radial mean free path $\lambda_r = 0.15 \text{ AU}$ and constant perpendicular mean free paths $\lambda_x = \lambda_y = 0.03 \text{ AU}$. Additionally, we adopt the SEP source function as in Equation (6). Due to the very dynamic interplanetary conditions, the realistic transport parameters and expressions should be more complicated. For example, in more accurate modeling of SEP transport, the pitch-angle dependence (e.g., Strauss & Fichtner 2015) and radial dependence (e.g., He & Wan 2012b) of the perpendicular diffusion coefficient should be taken into account. In spite of the simplified SEP model, the numerical calculation with perpendicular diffusion reproduces the counter-streaming particle beams with a deep depression of intensity at $\mu \sim 0$ during the onset phase, similar to what was detected by the Wind spacecraft. Our numerical investigation suggests that the perpendicular diffusion can be a possible mechanism for the formation of this SEP phenomenon. Basically, to observe a counter-streaming particle beam requires some specific conditions of the SEP event, such as a limited source, observers disconnected from the source, the diffusion processes (both parallel and perpendicular) of particles, and appropriate locations of the observers in the interplanetary magnetic field.

Another possible explanation for the formation of counter-streaming particle beams is

a combination of both the reflecting boundary mechanism and the perpendicular diffusion mechanism. As pointed out above, this explanation also requires a computationally tractable description of the reflecting boundaries.

5. Summary and Conclusions

In this work, we revisit the so-called counter-streaming particle beams observed in the SEP events and clarify some confusing results in the previous works. Our numerical simulations of SEP propagation with perpendicular diffusion in the three-dimensional interplanetary magnetic field reproduce the phenomenon of counter-streaming particle beams with a deep depression of flux at $\mu \sim 0$ during the onset phase of the SEP events. The comparison between the simulation results with and without perpendicular diffusion proposes that the perpendicular diffusion can be a possible mechanism responsible for the formation of the counter-streaming particle beams. Without exactly matching the timing of the SEP event, the simulation results with perpendicular diffusion show excellent agreement with the observation data. Therefore, the claim by Tan et al. (2012) that “the simulation result shown in Figure 3 of Qin et al. (2011) does not exhibit a particle depression at $\mu \sim 0$ as observed by Tan et al. (2009), contrary to their claim” is incorrect.

Our simulations with perpendicular diffusion reproduce the so-called counter-streaming particle beams with a deep depression of intensity at $\mu \sim 0$ during the onset phase without invoking the hypothesis of a reflecting boundary. It indicates that, at least, the reflecting boundaries are not the only possible reason causing the counter-streaming particle beams with a deep depression at $\mu \sim 0$ during the onset phase. Therefore, the counter-streaming particle beams with a deep depression at $\mu \sim 0$ during the onset phase cannot be used as strong evidence for the presence of the so-called outer reflecting boundaries in the interplanetary space.

This work was supported in part by grant Schl 201/29-1 of the Deutsche Forschungsgemeinschaft, the National Natural Science Foundation of China under grants 41204130, 41474154, 41321003, and 41131066, the National Important Basic Research Project under grant 2011CB811405, the Chinese Academy of Sciences under grant KZZD-EW-01-2, and the Open Research Program from Key Laboratory of Geospace Environment, Chinese Academy of Sciences. H.-Q. He gratefully acknowledges the support of the International Postdoctoral Exchange Fellowship Program of China under grant 20130023. We benefited from discussions at the team meeting “Exploration of the inner Heliosphere - what we have learned from Helios and what we want to study with Solar Orbiter”, supported by the International Space Science Institute (ISSI) in Bern, Switzerland. We benefited from the Wind/3DP data provided by Space Physics Research Group (SPRG), Space Sciences Laboratory (SSL), University of California at Berkeley (<http://sprg.ssl.berkeley.edu/wind3dp/>).

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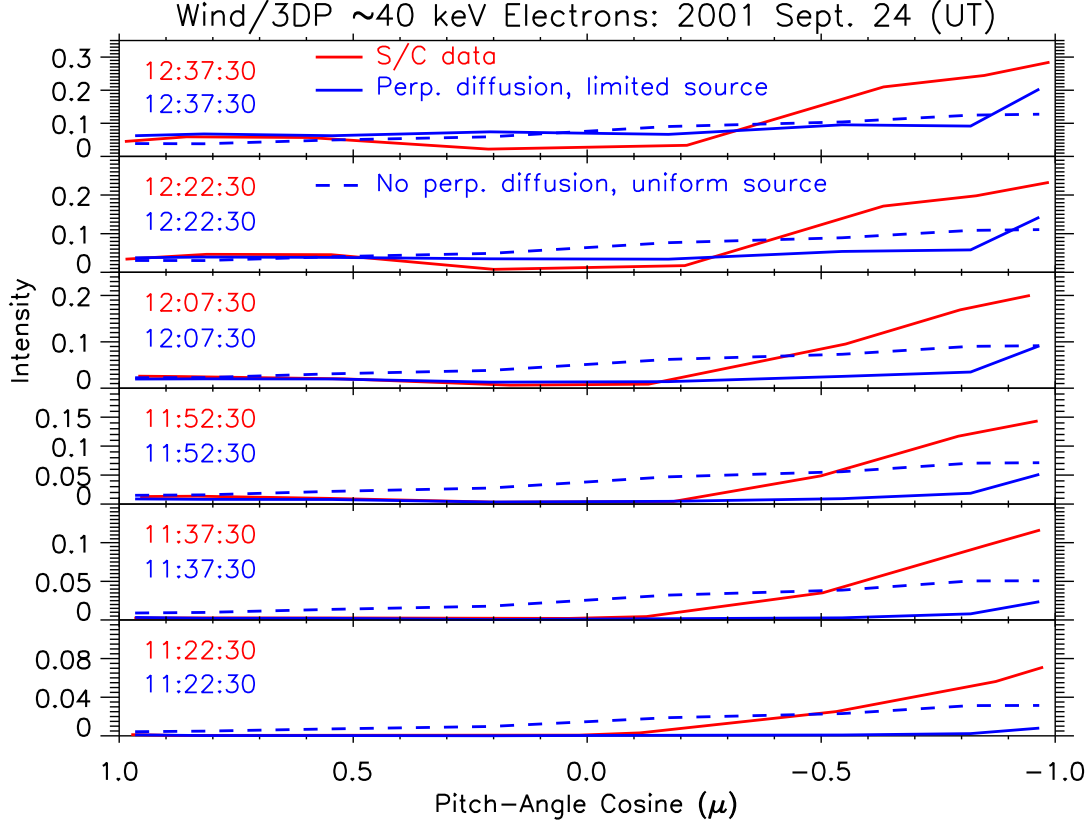


Fig. 1.— Temporal evolution (from bottom to top panels) of pitch-angle distributions of ~ 40 keV electrons during the beginning stage of the 2001 September 24 SEP event. In each panel, the red solid line indicates the spacecraft data; the blue solid and dashed lines indicate the simulation results with and without perpendicular diffusion, respectively. The simulation time (blue) in each panel is set to the exact same time as the observation time (red).

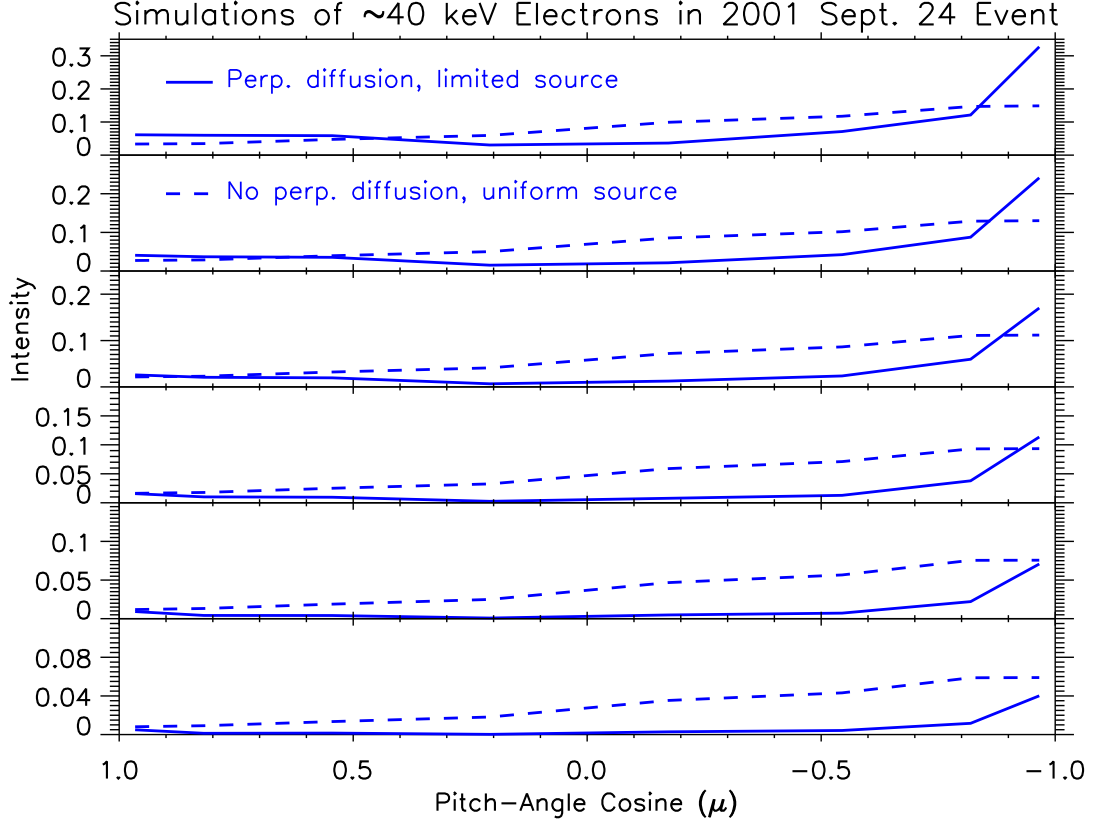


Fig. 2.— The simulation results are plotted in a rough-timing manner. The blue solid and dashed curves indicate the simulation results with and without perpendicular diffusion, respectively. The counter-streaming particle beam with deep depression at $\sim 90^\circ$ pitch angle is qualitatively reproduced in the simulation with perpendicular diffusion.

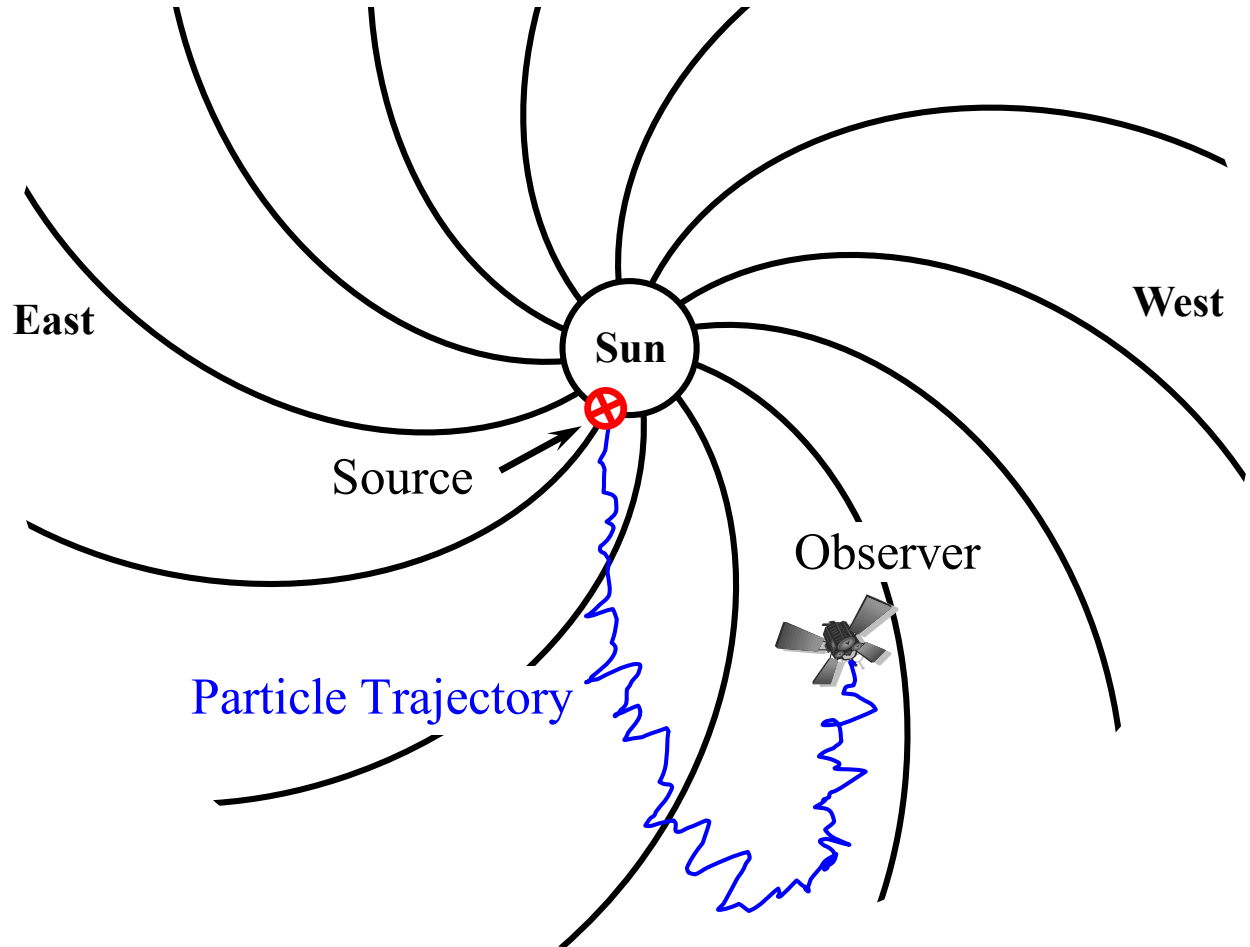


Fig. 3.— Illustration of the formation of counter-streaming particle beams in the interplanetary magnetic field.